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STRUCTURAL DYNAMICS SYSTEM MODEL REDUCTION

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Loads analysis for structural dynamic systems is usually performed by finite element models. Because of the complexity of the structural system, the model contains large number of degree-of-freedom. The large model is necessary since details of the stress, loads and responses due to mission environments are computed. However, a simplified model is needed for other tasks such as pre-test analysis for modal testing, and control-structural interaction studies. In the present report, a systematic method of model reduction for modal test analysis will be presented. Perhaps it will be of some help in developing a simplified model for the control studies.

The Test-Analysis Model (TAM) serves as the bridge between the loads model and the corresponding modal test whose purpose is to verify the validity of the loads model. It is obvious that the TAM must be compatible with the measurements of the modal test. Since instrumentation limitation, the TAM degrees-of-freedom will be much smaller than that of the loads analysis model.

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LOADS ANALYSIS MODEL REDUCTION

- Test Analysis Model (TAM) Requirement
- Pre-Test Analysis for Primary Modes Determination, Instrumentation Location Selection, Excitation Distribution and etc.
- Compatibility of DOF
- Test - Analysis Correlation
- Analytical Model Updating

These are the criteria for TAM.

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CRITERIA FOR REDUCED MODEL

- Accuracy in Frequency Prediction for Primary Modes
- Sufficient Resolution of Mode Shape Comparison
- Effective Mass - Completeness
- Accuracy With Respect to External Forcing Function
- Selection of DOF Based on Kinetic Energy

The governing equation begins at the spacecraft/launch vehicle coupled system.

GOVERNING EQUATIONS FOR PAYLOAD/LAUNCH VEHICLE COMPOSITE SYSTEM

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \left(\begin{bmatrix} k_1 & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} k_{11} & k_{21} \\ k_{12} & k_{22} \end{bmatrix} \right) \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} F(t) \\ 0 \end{Bmatrix}$$

$\{x_1\}$ = LAUNCH VEHICLE DEGREES-OF-FREEDOM (DOF)

$\{x_2\}$ = PAYLOAD DOF

$[m_1]$ = MASS MATRIX OF THE LAUNCH VEHICLE

$[m_2]$ = MASS MATRIX OF THE PAYLOAD

$[k_1]$ = STIFFNESS MATRIX OF THE LAUNCH VEHICLE

$[k_{11}]$, $[k_{12}]$, $[k_{21}]$, $[k_{22}]$ = SUB-MATRICES OF THE TOTAL PAYLOAD STIFFNESS MATRIX PARTITIONED INTO LAUNCH VEHICLE/PAYLOAD INTERFACE DOF AND PAYLOAD DOF.

$\{F(t)\}$ = EXTERNAL FORCING FUNCTION

Statically determinate interface between the spacecraft and launch vehicle is assumed.

STATICALLY DETERMINATE SUPPORTED PAYLOAD

$$\left.\begin{aligned} [k_{11}] &= [\phi_R]^T [k_{22}][\phi_R] \\ [k_{21}] &= -[\phi_R]^T [k_{22}] = [k_{12}]^T \end{aligned}\right\}$$

WHERE

$[\phi_R]$ = PAYLOAD RIGID BODY TRANSFORMATION MATRIX DEFINED AS THE PAYLOAD DISPLACEMENT DUE TO UNIT DISPLACEMENT OF THE LAUNCH VEHICLE/ PAYLOAD INTERFACE DOF, $\{X_I\}$.

$\{X_I\}$ = LAUNCH VEHICLE/PAYLOAD INTERFACE DOF CONNECTING PAYLOAD TO LAUNCH VEHICLE, A SUBSET OF THE LAUNCH VEHICLE DOF $\{X_I\}$.

The spacecraft responses are decomposed into rigid-body motion and elastic motion. It should be noted that only the elastic motion will cause structural loads.

PAYLOAD MOTION DECOMPOSITION

$$\{x_2\} = [\phi_R]\{x_I\} + \{x_e\}$$

$$\begin{bmatrix} m_1 + m_{rr} & \phi_R^T m_2 \\ m_2\phi_R & m_2 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_e \end{Bmatrix} + \begin{bmatrix} k_1 & 0 \\ 0 & k_{22} \end{bmatrix} \begin{Bmatrix} x_1 \\ x_e \end{Bmatrix} = \begin{Bmatrix} F(t) \\ 0 \end{Bmatrix}$$

WHERE

$$[m_{rr}] = [\phi_R]^T [m_2][\phi_R]$$

DENOTED AS RIGID-BODY MASS.

The accuracy of the response is dependent on the selection of modes. The modes selection should be based on the criteria of providing maximum response, frequency sensitive to the forcing functions and maximum effective mass. The TAM should produce modes which will satisfy all these criteria.

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GENERALIZED COORDINATES

$$[m]\{\ddot{x}\} + [k]\{x\} = -[m_2][\phi_R]\{\ddot{x}_I\} \longleftarrow \text{FULL DOF MODEL}$$

LET $\{x\} = [\phi]\{u(t)\} \longleftarrow$ **MODAL TRUNCATION**
SELECT MODES FOR MAX. X

WHERE $[\phi]$ IS THE NORMAL MODE MATRIX SUCH THAT

$$[\phi]^T[m][\phi] = [\diagdown I \diagdown], \text{ IDENTITY MATRIX}$$

$$[\phi]^T[k][\phi] = [\diagdown \omega^2 \diagdown], \text{ EIGENVALUE}$$

$$\{\ddot{u}\} + [\diagdown 2\rho\omega \diagdown]\{\dot{u}\} + [\diagdown \omega^2 \diagdown]\{u\} = \{F(t)\}$$

SELECT MODES SENSITIVE TO F(t)

WHERE

$$\{F(t)\} = -[\phi]^T[m_2][\phi_R]\{\ddot{x}_I\} = \text{GENERALIZED FORCE}$$

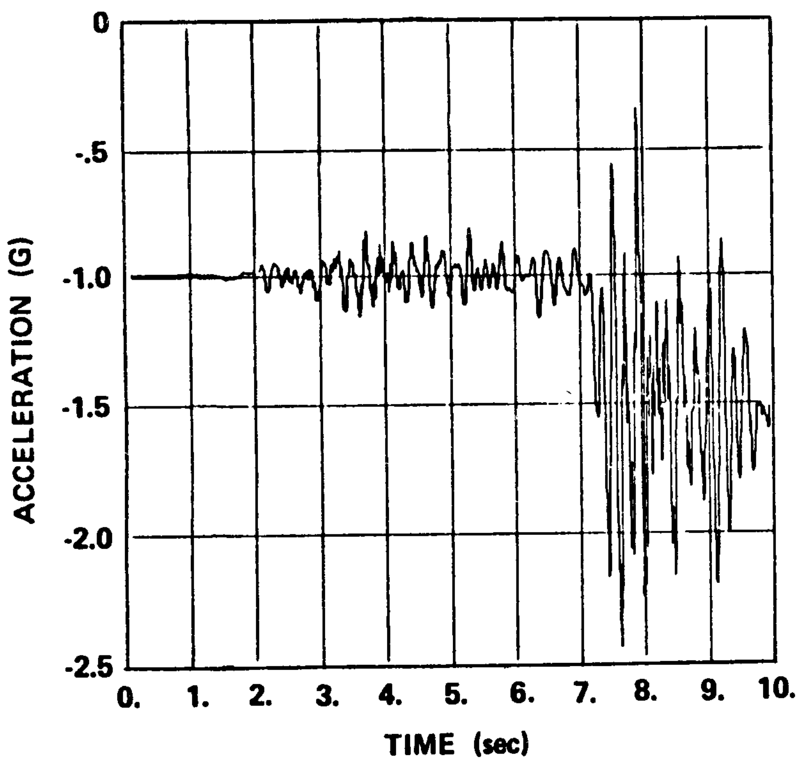
$$= -[M_{er}]\{\ddot{x}_I\}$$

RELATED TO EFFECTIVE MASS

This is a typical forcing function in the form of interface acceleration. The shock spectra indicates that that modes with frequency either lower than 2.0 Hz or higher than 40.0 Hz will be of little effect as far as response calculation is concerned.

LAUNCH VEHICLE/SPCECRAFT
INTERFACE ACCELERATION
LONGITUDINAL (Z) DIRECTION

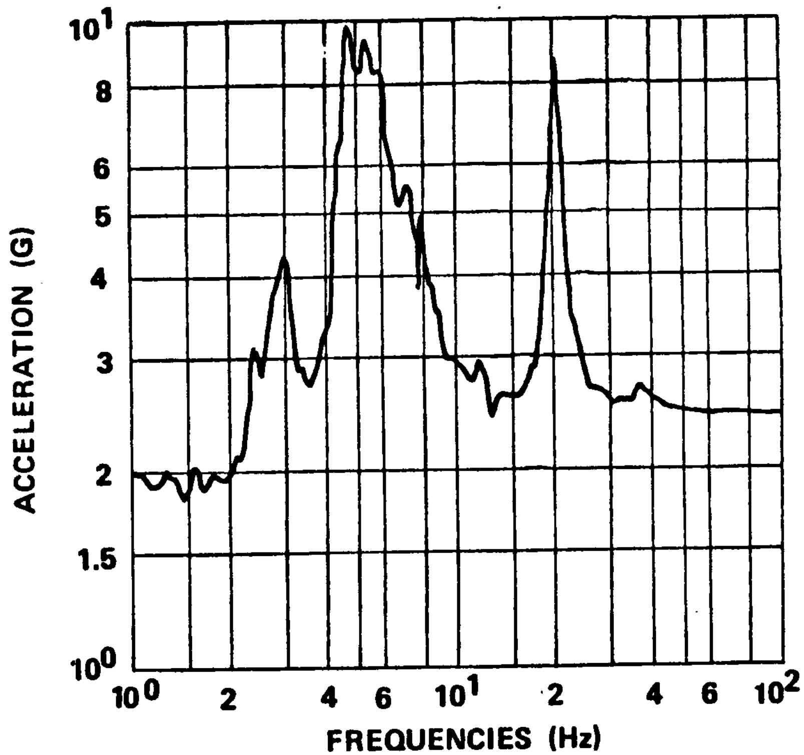
TIME HISTORY



DATA SET = 3

STIFF1 GLL86 + L/V 7301 0 TUNE -I/F Z

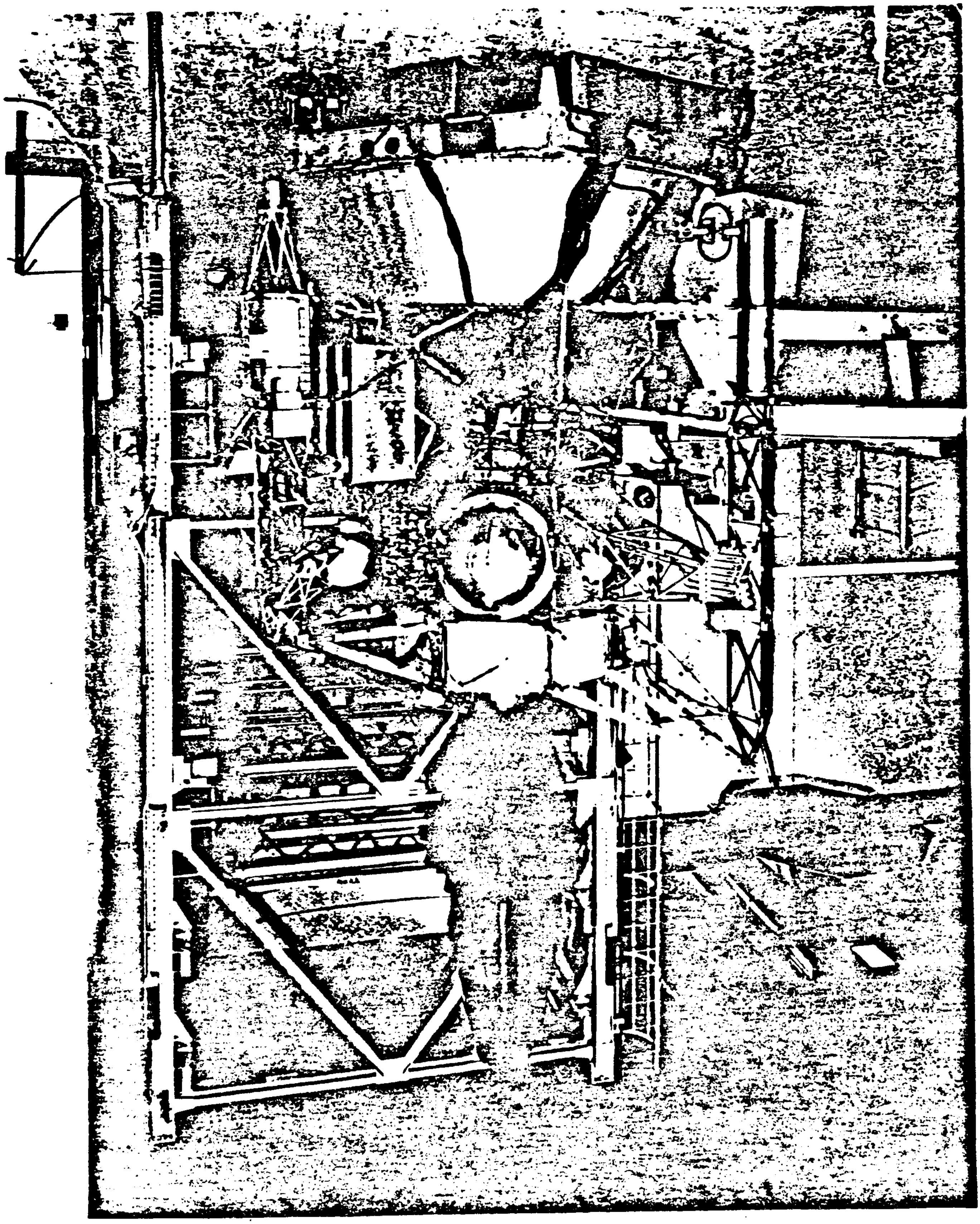
SHOCK SPECTRA



DATA SET = Q = 50

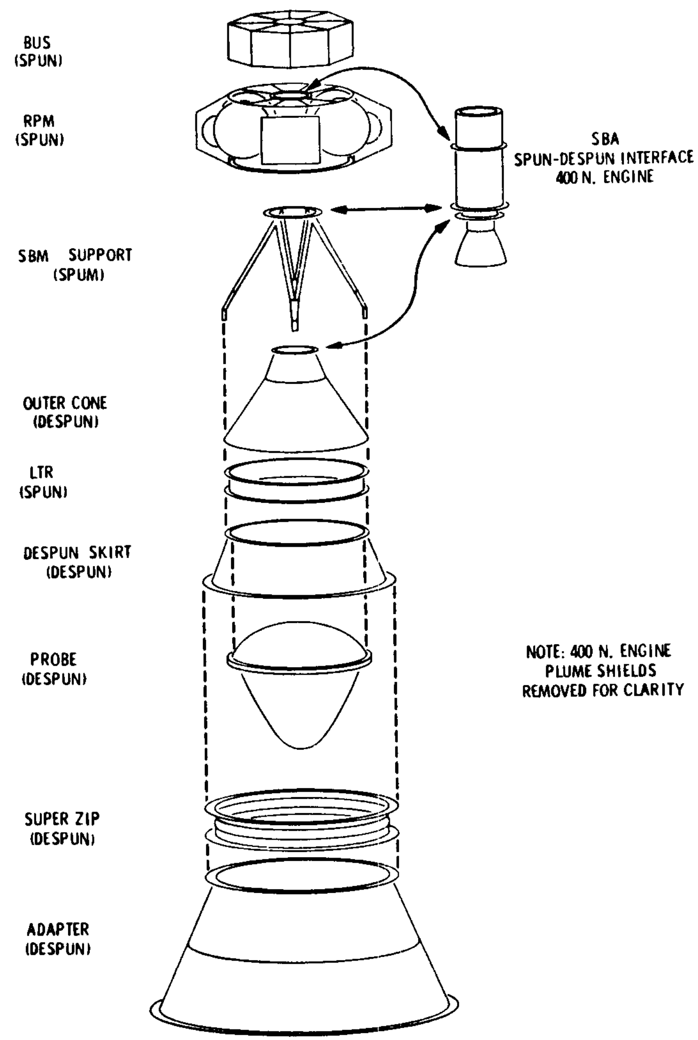
STIFF1 GLL86 + L/V 7301 0 TUNE -I/F Z

The model reduction procedure will be demonstrated by the Galileo spacecraft.



The Galileo spacecraft has a complex structural system. A detailed finite element model is required for the loads analysis.

GALILEO SPACECRAFT CORE STRUCTURES



This shows weight distribution of the subsystems.

GALILEO SPACECRAFT MAJOR SUBSYSTEMS

Subsystem	Mass* (kg)	Weight* (lbs)
High Gain Antenna	49.5	109.1
Bus	272.5	600.7
Retro Propulsion Module (RPM)	1216	2681
Despun Box	110.4	243.3
RRH	6.0	13.2
Bay E	14.5	32.0
Science Boom	76.6	168.8
Scan Platform	96.4	212.5
+x RTG	80.2	176.9
-x RTG	77.2	170.2
Probe	341.8	753.4
Spin Bearing	43.1	95.1
Inner Cone		
LTR		
Despun Cone	52.8	116.3
S/C Adapter	50.1	110.6

The final loads model contains 10,000 degrees-of-freedom.

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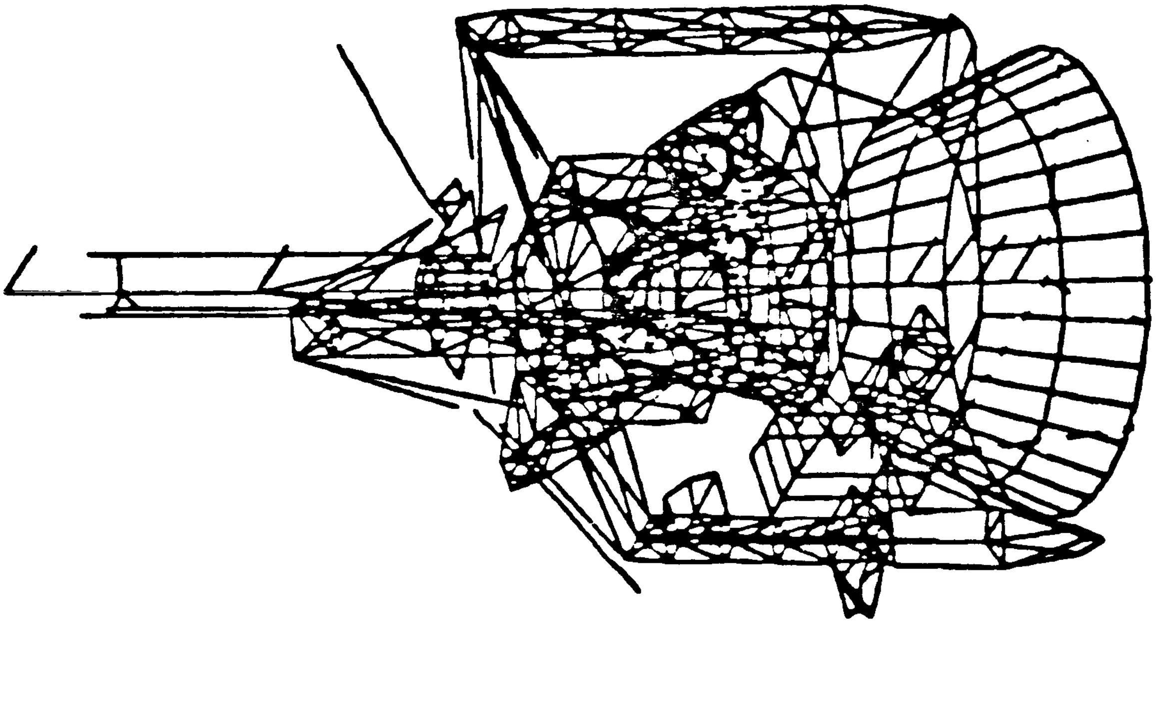
GALILEO NASTRAN MODEL



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These are the frequencies predicted by the loads model.

FREQUENCY PREDICTION

MODE NO.	FREQ (Hz)	MODE NO.	FREQ (Hz)	MODE NO.	FREQ (Hz)
1	12.78	25	37.49	49	53.42
2	13.04	26	38.48	50	53.90
3	16.59	27	40.22	51	54.58
4	17.45	28	40.54	52	56.02
5	18.42	29	41.34	53	56.45
6	19.36	30	41.60	54	56.76
7	19.77	31	41.93	55	63.35
8	20.86	32	42.09	56	63.89
9	21.94	33	42.16	57	65.07
10	22.69	34	42.25	58	67.94
11	22.88	35	42.33	59	68.35
12	28.01	36	42.78	60	69.04
13	29.11	37	43.38	61	69.94
14	29.51	38	43.48	62	71.02
15	31.17	39	44.08	63	71.63
16	31.44	40	45.23	64	72.56
17	31.44	41	47.25	65	73.38
18	31.90	42	48.43	66	75.04
19	33.44	43	48.89	67	76.07
20	34.57	44	49.74	68	76.55
21	35.21	45	49.98	69	80.19
22	35.99	46	50.23	70	82.88
23	36.07	47	50.89		
24	36.47	48	51.38		

This is the description of the first six modes.

MODES DESCRIPTION

MODE No.	FREQ (Hz)	DESCRIPTION
1	12.78	GLOBAL BENDING IN x-DIRECTION. +x & -x RTG MOTION IN +z & -z DIRECTION RESPECTIVELY, WALKING MODE
2	13.04	GLOBAL BENDING IN y-DIRECTION
3	16.59	LOCAL MODE, MAG. CAN. MOTION IN y-DIRECTION, -x RTG MOTION IN z-DIRECTION
4	17.45	2nd GLOBAL BENDING IN y-DIRECTION
5	18.42	2nd GLOBAL BENDING IN x-DIRECTION
6	19.36	LOCAL MODE, BOTH MAG. CAN. & -x RTG IN z-DIRECTION MOTION, IN PHASE

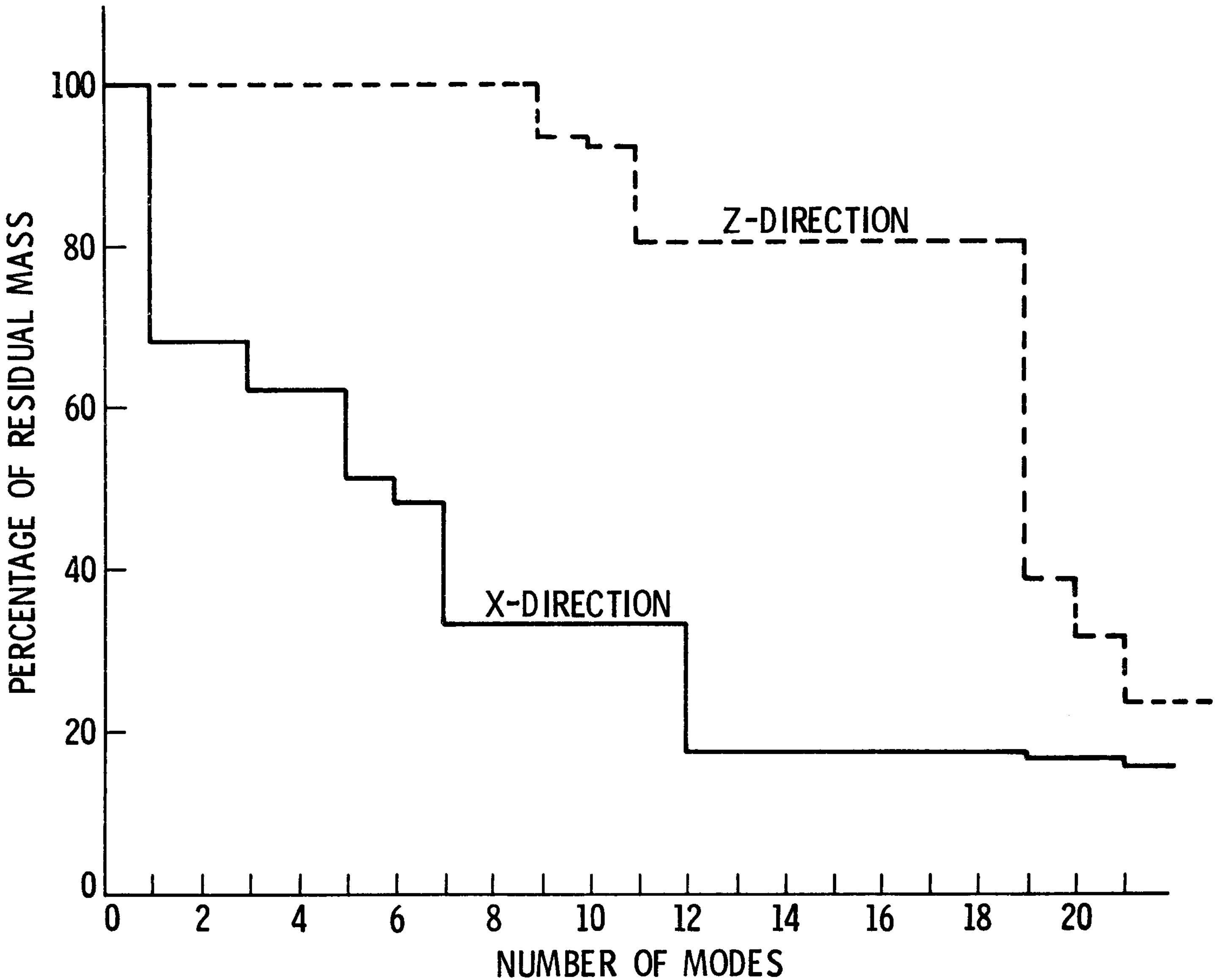
These are the predicted effective mass in percentage. Those modes with large effective mass are the important modes for the loads analysis and should be predicted by the reduced model. It should be noted that the total effective mass for the first 21 modes constitutes only a portion of the total mass.

EFFECTIVE MASS

MODE \ DOF	x	y	z	θ_x	θ_y	θ_z
1	.3239	.0046	.0001	.0067	.6701	.0007
2	.0028	.3519	.0002	.6678	.0067	0
3	.0569	.0018	.0001	.0005	.0189	.2719
4	.0038	.3392	.0004	.2434	.0024	.0009
5	.1135	.0018	0	.0015	.1118	.0130
6	.0343	.0844	.0016	.0143	.0204	.0008
7	.1520	.0026	.0003	0	.0813	.0171
8	.0031	.0003	.0021	.0005	.0002	.2785
9	0	.0006	.0723	.0024	.0001	.0098
10	.0001	.0005	.0117	.0003	0	0
11	.0001	.0012	.1225	.0013	0	.0021
12	.1453	.0002	.0020	0	.0395	.0141
13	.0006	.0008	0	.0001	.0004	.0037
14	.0007	.0067	0	.0011	.0001	.0009
15	0	0	0	0	0	0
16	0	0	0	0	0	0
17	0	0	0	0	0	0
18	.0001	.0004	.0002	0	.0001	.0009
19	.0059	.0030	.4144	.0002	.0015	0
20	.0009	.0051	.0642	.0001	.0002	.0007
21	.0048	.0010	.0738	.0001	.0011	.0001
SUM	.8488	.8061	.7659	.9403	.9548	.6152

The residual mass is defined as the total mass subtracted by the effective mass. The smaller residual mass is an indication for a better modal truncation.

RESIDUAL MASS



The modal accelerations due to a typical interface acceleration are calculated for the first 21 modes. They are shown here together with the sum of the effective mass. In general, modes with higher effective mass will have higher modal accerlations and they are the important modes. However, there are some modes with smaller effective mass but large modal accelerations such as the 19th mode. These modes may be local modes but they may generate higher loads for the local structures. Therefore, they should be considered as important modes too.

MODAL ACCELERATION

MODE	FREQ (Hz)	EFFECTIVE MASS SUMMATION	MODAL ACCELERATION
1	12.78	1.01	2.00 (g)
2	13.04	1.03	8.52
3	16.59	.35	-1.36
4	17.45	.59	-8.14
5	18.42	.24	1.19
6	19.36	.16	3.15
7	19.77	.25	-1.62
8	20.86	.29	-1.33
9	21.94	.09	4.25
10	22.69	.01	-1.39
11	22.88	.13	4.42
12	28.01	.20	-2.26
13	29.11	.01	.21
14	29.51	.01	.60
15	31.17	0	0
16	31.44	0	-.07
17	31.44	0	-.06
18	31.90	0	-.20
19	33.44	.43	6.35
20	34.57	.07	2.46
21	35.21	.08	2.75

As mentioned before, the kinetic energy distribution will be used as the basis for selecting the degree-of-freedom for the reduced model. For this particular mode, the kinetic energy is distributed with 36.20% in x-direction, 40.43% in y-direction and 22.15% in z-direction, a relatively uniform distribution. The degree-of-freedom with higher kinetic energy is indicated. Because of the relatively uniform distribution of kinetic energy, we conside this mode to be a global mode.

JPL KINETIC ENERGY DISTRIBUTION FOR GLOBAL MODE

KINETIC ENERGY FOR MODE 7 JPL DATA

GRID	DOF	X	Y	Z	RX	RY	RZ	
119		0.0039	0.0018					0.0056
379		0.0020	0.0001	0.0008				0.0030
841		$\boxed{0.1195}$	$\boxed{0.0908}$	0.0000				$\boxed{0.2103}$
2130		0.0131	0.0177	0.0038				0.0346
2340		0.0219	0.0404	0.0008				0.0631
2530		0.0129	0.0187	0.0060				0.0377
2740		0.0289	0.0350	0.0011				0.0650
3075		0.0011	0.0012	0.0005				0.0027
3076		0.0007	0.0013	0.0006				0.0026
3160		$\boxed{0.0389}$	$\boxed{0.0524}$	0.0159	0.0001	0.0001	0.0000	$\boxed{0.1074}$
3260		0.0212	0.0288	0.0000	0.0001	0.0000	0.0000	0.0501
3360		0.0303	0.0397	0.0171	0.0001	0.0001	0.0000	0.0873
3460		0.0172	0.0250	0.0000	0.0001	0.0000	0.0000	0.0423
3550		0.0013	0.0016	0.0007				0.0037
3555		0.0008	0.0012	0.0034	0.0000			0.0054
3650		0.0014	0.0017	0.0006				0.0037
3665		0.0009	0.0015	0.0035	0.0000			0.0059
4123		0.0009	0.0007	0.0001				0.0017
4128		0.0013	0.0002	0.0011				0.0025
4235		0.0013	0.0001	0.0003				0.0017
4401		0.0000						0.0000
4418		0.0003	0.0033	0.0007	0.0000	0.0000		0.0043
5001		0.0035	0.0078	0.0040				0.0154
5004		0.0048	0.0000	0.0095				0.0144
5008		0.0045	0.0036	0.0042				0.0123
5009		0.0002	0.0001	0.0007				0.0010
5050				0.0011				0.0011
5052		0.0030		0.0011				0.0041
5072				0.0013				0.0013
5092		0.0019		0.0018				0.0037
5111		0.0019	0.0000	0.0046				0.0065
5112		0.0019	0.0006	0.0038				0.0063
5115		0.0035	0.0001	0.0056				0.0092
5604		0.0003	0.0000					0.0003
5610		0.0001	0.0000					0.0001
6002		0.0002		0.0001				0.0005
6003				0.0001				0.0001
6100		0.0002	0.0007	0.0013	0.0004	0.0000	0.0001	0.0026
6205				0.0004				0.0004
7050		0.0000	0.0001	0.0089	0.0006	0.0001	0.0000	0.0097
7550		0.0000	0.0001	$\boxed{0.1155}$	0.0002	0.0009	0.0000	$\boxed{0.1165}$
8050		0.0154	0.0200	0.0000	0.0032	0.0033	0.0000	0.0419
8060		0.0000	0.0000	0.0000	0.0000	0.0000		0.0001
8130		0.0005	0.0077	0.0002	0.0016	0.0010	0.0002	0.0112
9104		0.0000	0.0000					0.0000
9114		0.0000	0.0002					0.0003
9125		0.0002	0.0000					0.0002
9404		0.0000	0.0000					0.0000
9414		0.0000	0.0000					0.0000
9425		0.0000	0.0000					
		0.3620	0.4043	0.2215	0.0064	0.0056	0.0002	1.0000

For this mode, almost all the kinetic energy is concentrated at one degree-of-freedom which is a good indication for a local mode.

KINETIC ENERGY DISTRIBUTION FOR LOCAL MODE

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KINETIC ENERGY FOR MODE 10 JPL DATA

GRID	DOF X	Y	Z	RX	RY	RZ	
119	0.0000	0.0000					0.0000
379	0.0000	0.0000	0.0000				0.0000
841	0.0000	0.0000	0.0000				0.0000
2130	0.0000	0.0000	0.0000				0.0000
2340	0.0000	0.0001	0.0000				0.0001
2530	0.0000	0.0002	0.0000				0.0002
2740	0.0000	0.0001	0.0000				0.0001
3075	0.0000	0.0000	0.0000				0.0000
3076	0.0000	0.0000	0.0000				0.0000
3160	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0001
3260	0.0002	0.0002	0.0000	0.0000	0.0000	0.0000	0.0004
3360	0.0000	0.0001	0.0002	0.0000	0.0000	0.0000	0.0003
3460	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
3550	0.0000	0.0000	0.0000				0.0000
3555	0.0000	0.0001	0.0000	0.0000			0.0001
3650	0.0000	0.0000	0.0000				0.0000
3665	0.0000	0.0001	0.0000	0.0000			0.0001
4123	0.0000	0.0000	0.0000				0.0000
4128	0.0000	0.0000	0.0000				0.0000
4235	0.0000	0.0000	0.0000				0.0000
4401	0.0000						0.0000
4418	0.0000	0.0000	0.0000	0.0000	0.0000		0.0000
5001	0.0000	0.0000	0.0001				0.0001
5004	0.0000	0.0000	0.0005				0.0005
5008	0.0000	0.0000	0.0003				0.0003
5009	0.0000	0.0000	0.0001				0.0001
5050			0.0001				0.0001
5052	0.0000		0.0001				0.0001
5072			0.0001				0.0001
5092	0.0000		0.0001				0.0001
5111	0.0000	0.0000	0.0004				0.0004
5112	0.0000	0.0000	0.0004				0.0004
5115	0.0000	0.0000	0.0004				0.0004
5604	0.0000	0.0000					0.0000
5610	0.0000	0.0000					0.0000
6002	0.0006		0.0018				0.0024
6003			0.0015				0.0015
6100	0.0006	0.0002	0.0046	0.0012	0.0000	0.0004	0.0070
6205			$\boxed{0.9799}$				$\boxed{0.9799}$
7050	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7550	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
8050	0.0000	0.0000	0.0000	0.0008	0.0000	0.0000	0.0008
8060	0.0000	0.0001	0.0000	0.0000	0.0000		0.0001
8130	0.0000	0.0036	0.0000	0.0000	0.0000	0.0000	0.0036
9104	0.0000	0.0000					0.0000
9114	0.0000	0.0000					0.0000
9125	0.0001	0.0000					0.0001
9404	0.0000	0.0000					0.0000
9414	0.0000	0.0000					0.0000
9425	0.0000	0.0000					
	0.0017	0.0050	0.9909	0.0020	0.0000	0.0004	1.0000

The degrees-of-freedom with more than 5.0% of kinetic energy in any of the important modes are retained for the reduced model, TAM. A total of 162 degrees-of-freedom are retained out of 10,000 degrees-of-freedom.

TAM PREDICTION

Mode	Frequencies (Hz)	Description
1	13.22	Global bending in X
2	13.44	Global bending in Y
3	16.93	Science boom in X
4	17.90	SXA in Y
5	18.89	SXA in X
6	19.92	-X RTG in Z
7	20.58	+X RGG in Z
8	21.46	Oxidizer 2 in X-Y
9	22.67	±X RTG in Z
10	23.62	Probe in Y
11	28.69	Science in Y
12	29.76	Damper and Science Boom in Y
13	30.26	SXA Local in X-Y
14	31.38	SXA Local in X
15	32.40	SXA Local in Y
16	32.69	Probe in X
17	33.15	Damper in X
18	34.26	Oxidizer in Z
19	36.06	Relay Antenna in Y
20	36.53	Thruster Boom in Y
21	37.35	Thruster Boom in Y

The results of the reduced model, TAM, are compared with those of the loads model. Excellent agreement is obtained. It is concluded that this systematic procedure for model reduction will provide a good representation for a large complex model.

FREQUENCY AND EFFECTIVE MASS COMPARIONS FOR TAM AND LOADS MODEL

TAM			Loads Model		
Mode	Freq (Hz)	Eff. Mass (kg)	Mode	Freq (Hz)	Eff. Mass (kg)
1	13.22	796.0	1	13.23	786.2
2	13.44	840.0	2	13.50	841.0
3	16.93	142.5	3	16.94	143.4
4	17.90	858.0	4	17.99	852.0
5	18.89	291.0	5	18.98	281.0
6	19.92	293.0	6	19.93	298.0
7	20.58	391.1	7	20.39	395.8
8	21.46	6.0	8	21.47	10.1
9	22.67	120.2	9	22.60	176.2
10	23.62	394.0	10	23.54	391.1
11	28.69	344.6	11	28.84	360.3
13	30.26	15.9	13	30.34	16.6
18	34.26	1091.5	18	34.40	1043.8
23	37.69	55.1	19	35.56	17.1
19	36.06	345.2	20	36.18	176.2
22	37.33	5.9	21	36.76	25.1